Nano World Journal

https://doi.org/10.17756/nwj.2023-s1-036

Research Article

Open Access

Modelling and Parametric Analysis of WEDM Process of Heat-treated Magnesium Alloy

Dhirendra Pratap Singh*, Chandra Prakash Pandey* and Sanjay Mishra

Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, India

*Correspondence to:
Dhirendra Pratap Singh
Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, India.
E-mail: dhirendrapratapsingh043@gmail.com

Chandra Prakash Pandey
Madan Mohan Malaviya University of Technology, Gorakhpur, Uttar Pradesh, India.
E-mail: pandeycp1311@gmail.com

Received: November 24, 2022
Accepted: April 08, 2023
Published: April 10, 2023

Citation: Singh DP, Pandey CP, Mishra S. 2023. Modelling and Parametric Analysis of WEDM Process of Heat-treated Magnesium Alloy. *NanoWorld J* 9(S1): S176-S181.

Published by United Scientific Group

Abstract

The magnesium alloy AZ31 is frequently utilized in aerospace and medical industries. Since its density is similar to human bone, it is widely used in medical science and other related areas. In this study, 10 mm thick workpieces of AZ31 were heat treated in a muffle furnace at 400 °C for 3 and 5 hours respectively after which it was normalized to room temperature. Experiments were conducted based on the Box Behnken Design (BBD) approach of Response Surface Methodology (RSM) and second order regression model was developed based on the experimental data to find the correlation of pulse-on time, pulse-off time, and current with output parameters i.e., cutting velocity (CV) and surface roughness (SR). Parametric analysis using response surface plots reveals that CV continuously decreases when pulse on time (T_{on}) increases whereas increase of current (I) led to continuous rise of CV. WEDM (wire electrical discharge machine) of magnesium alloy yields better surface finish at lower value of both T_{on} and T_{off} (pulse off time).

Keywords

AZ31, Analysis of variance, Wire electrical discharge machine, Cutting velocity, Surface roughness

Introduction

Magnesium (Mg) and its alloy were widely used in aerospace, automotive industries, and medical science due to their low-density, low weight, and higher mechanical strength. But due to the typically hexagonal closed packed structure at room temperature, it shows insufficient strength and a higher corrosion rate [1]. To increase the strength and minimize corrosion rate many authors heat-treated this Mg alloy to increase the properties by changing microstructural behavior [2].

Zhang et al. explored that due to the coating phytic acid conversions and heat treating from 150 °C to 400 °C the mechanical strength and corrosion resistance of AZ31 alloy have been increased [3]. Das et al. who make magnesium strips by twin roll casting and melt condition twin roll casting discovered that the tensile characteristics were nearly equal. Although twin roll casting samples had larger grains than melt condition twin roll casting samples [4]. Koklu et al. passed an Mg alloy through an extrusion process, due to a change in microstructural grain it improves the mechanical properties and decreases ductility [5].

Goyal et al. cut a workpiece of AZ31 alloy of size 10 mm x 10 mm x 6 mm from 200 mm x 200 mm x 6 mm. And use the BBD approach of RSM for experimental design by considering T_{on}, servo feed, servo voltage, and T_{off} as input parameters for recast layer thickness and cutting rate and found that T_{on} was the most influencing parameter for cutting rate and recast layer thickness [6]. Tapadar et al. did their experiment on Mg metal matrix composites which were prepared by mixing 5% SiC on WEDM and found that T_{on} and T_{off} were the most influencing parameters for material removal rate (MRR) and SR [7]. Vijayabhaskar et al. also found that T_{on} and voltage have a significant effect on MRR, due to an increment in voltage increases discharge energy due to this more material melted so MRR increases [8]. Many authors use the BBD approach of RSM for experimental design and use ANOVA (analysis of variance) for finding the significant interaction of input parameters on output responses [9-11].

From the literature survey it is clear that no work has been reported for parametric analysis of WEDM for heat treated AZ31 alloy. Therefore, in this work, an experimental investigation was performed on 10 mm thick AZ31 Mg alloy heat treated for 3 and 5 hours at 400 °C. To perform experiment T_{on}, T_{off}, and I were considered as input parameters for CV and SR as an output response. And a significant combination of input parameters for SR and CV was predicted by the ANOVA. Simultaneous effects of two different input parameters on CV and SR were analyzed using RSM plots.

Experimental Setup and Preparation of Material

Heat treatment of materials

In this work, two AZ31 Mg alloy of 10 mm thickness were used to perform the experiment. Before using the material for the experiment, it passed through the heat treatment process. AZ31 Mg alloy has hexagonal closed packed structure at room temperature; therefore, it possesses insufficient strength and a higher corrosion rate. Heat treatment of AZ31 results in enhancement of shear strength of material and thus reducing the formation of cracks during machining. For the treatment of material, we use a muffle furnace whose maximum temp is 1400 °C shown in figure 1. We use three stages of the heat treatment process i.e., Heating, Soaking, and Cooling. Firstly, during the heating process, we heated the Workpiece in the Furnace and when it achieves 400 °C then for soaking maintain at this temperature one for 3 hours and 2nd for 5 hours. After completing the soaking time, we took out the workpiece from the furnace to cool down in ambient air. And further use for the experiment. Table 1 and table 2 show the material properties and chemical composition of AZ31.

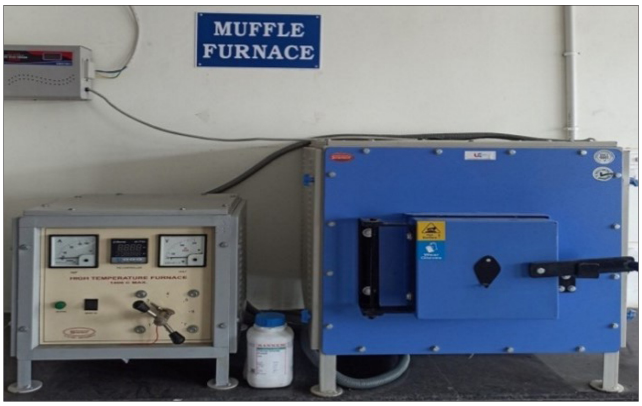

Figure 1: Muffle furnace.

Table 1: Properties of work material AZ31 [6].

Properties	Unit	Value
Tensile strength	MPa	259
Coefficient of thermal expansion	µm/m °C	26
Thermal conductivity	W/mK	95
Density	g/cm^3	1.76
Modulus of elasticity	GPa	46
Poisson's ratio	-	0.36
Hardness	HRB	50

Table 2: Chemical composition of AZ31 [6].

Chemical	Mg	Ni	Ca	Fe	Si	Cu	Mn	Zn	Al
Percentage	Balance	0.005	0.04	0.005	0.1	0.005	0.04	0.005	3.4

Experimentation

For the experiment we use the CNC wire cut EDM (model no - EX5040C) shown in figure 2. Even though the machineability of Mg alloy AZ31 using conventional machining methods is good but it produces built up edge and chattering of tools occurs during machining due to which geometrical tolerance of the machined surface deteriorates. Therefore, all such applications where tight geometrical tolerance is required with good surface finish is required, the conventional machining would not produce the desired performance characteristics quality. Hence, the WEDM process in which material is removed by controlled thermal erosion is preferred for machining of AZ31 alloy [12]. During experiment on WEDM few parameters were kept constant shown in table 3. To perform the experiment, we use three process parameters at three levels such as T_{on}, T_{off}, and I for CV and SR as output responses which are shown in table 4. The machining was performed by reciprocating molybdenum wire of 0.18 mm diameter whose properties are given in following table 5. For the experiment, we cut a rectangle of 10 mm x 1 mm x 10 mm.

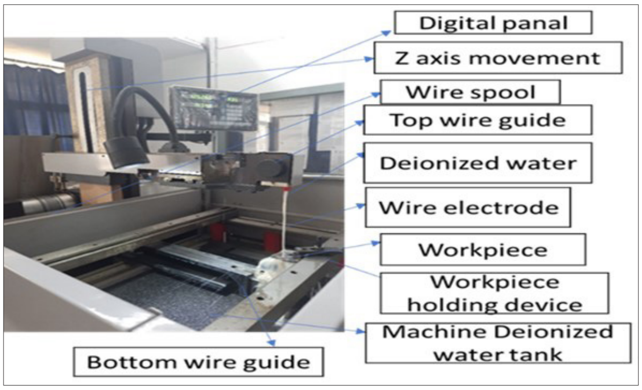

Figure 2: Wire electrical discharge machine.

Measurements

To measure the CV, we use the length of cut per unit time which is shown in equation 1. Since during cutting a rectangle of 10 mm x 1 mm wire need to travel 21 mm (10 +

Table 3: Parameters held constant during the experiments.

Parameters	Values
Electrode material	Molybdenum wire of 0.18 mm diameter
Voltage	Low voltage (~70 - 75 V)
Workpiece material	AZ31 HT at 3H/ AZ31 HT at 5H
Wire speed	10.4 m/sec
Wire tension	Constant

Table 4: Process parameters for WEDM and their levels.

Input parameters	Symbol	Units	Level		
			-1	0	+1
Pulse on time	T_{on}	µs	30	40	50
Pulse off time	T_{off}	µs	6	9	12
Current	I	amp	1	3	5

Table 5: Physical and mechanical properties of molybdenum wire [13].

Properties	Unit	Value
Density (at 20 °C)	g/cm^3	10.3
Modulus of elasticity	GPa	330
Electrical conductivity	S/m	1.73×10^{-7}
Heat conductivity	W/mK	138
Melting point	°C	2625
Thermal expansion coefficient at 25 °C	cm/cm	5.0×10^{-6}

1 + 10). Taylor Hobson made a surface roughness tester that was used to determine the SR.

$$CV = \frac{\text{length of cut (mm)}}{\text{machining time (time)}} \quad (1)$$

Response surface modelling

It is a statistical modelling tool that establishes a relationship between the input and output variables. In this study, the experimental design was developed using the BBD approach of RSM. This design reduces the number of experiments by considering all input parameters and gives accurate results. The number of experiments required in the BBD technique is K= 2p (p-1) + $q_{0,}$ where q_0 is the number of central point's necessary to maintain the iso-variance and orthogonality and p is the number of input parameters. Since there were three input parameters and three center points in this case, there were a total of 15 experimental designs, as shown in table 6 with the experimental results for the AZ31b heat-treated at three and five hours.

$$P_x = Q_0 + \sum_{i=1}^{n} Q_i r_{iu} + \sum_{i=1}^{n} Q_{ii} r_{iu}^2 + \sum\sum_{i<j}^{n} Q_{ij} r_{iu} r_{ju} \pm Z_u \quad (2)$$

Where, Q_0 = constant; Q_i = regression coefficients of linear; Q_{ii} = regression coefficients of quadratic; Q_{ij} = regression coefficients of interaction terms; r_{iu} = i^{th} machining parameters' encoded values for the u^{th} experiment; Z_u = the experimental error of the u^{th} observations.

RSM models for AZ31 HT 3 hours and 5 hours

For a 3-hour heat treatment Mg alloy material at 400 °C, the CV and SR of AZ31 are represented by the 2^{nd} order regression model in equation 3 and equation 4, respectively. And for a 5-hour heat treatment Mg alloy material at 400 °C, the CV and SR of AZ31 are represented by the 2^{nd} order regression model in equation 5 and equation 6, respectively.

$$CV\ (mm/min) = 1.56 + 0.143\ T_{on} + 0.326\ T_{off} + 0.618\ I - 0.00332\ T_{on} * T_{on} - 0.0156\ T_{off} * T_{off} - 0.2450\ I * I - 0.00047\ T_{on} * T_{off} + 0.03517\ T_{on} * I - 0.0089\ T_{off} * I \quad (3)$$

$$SR\ (\mu m) = -11.99 + 0.482\ T_{on} + 1.296\ T_{off} + 1.175\ I - 0.00348\ T_{on} * T_{on} - 0.0305\ T_{off} * T_{off} - 0.1940\ I * I - 0.01742\ T_{on} * T_{off} + 0.00471\ T_{on} * I + 0.0129\ T_{off} * I \quad (4)$$

Table 6: Response table of experiment for AZ31 for HT 3 and 5 hours.

Exp No	Pulse on time	Pulse off time	Current	AZ31 HT 3 hours		AZ31 HT 5 hours	
				CV	SR	CV	SR
	(T_{on})	(T_{off})	(I)	(mm/min)		(mm/min)	
1	30	6	3	6.6108	5.15	6.7742	6.3933
2	50	6	3	6.717	7.3333	6.8755	5.6467
3	30	12	3	6.6021	7.1433	6.6804	5.6133
4	50	12	3	6.6516	7.2367	6.8077	7.51
5	30	9	1	6.1463	5.0433	6.2539	5.6767
6	50	9	1	3.8298	6.1567	4.0457	5.8767
7	30	9	5	6.3742	6.0833	6.8168	6.2933
8	50	9	5	6.8714	7.5733	6.8535	7.4733
9	40	6	1	4.8412	5.6533	5.2674	5.59
10	40	12	1	4.9874	5.6267	4.7456	5.51
11	40	6	5	7.1131	6.7933	6.9835	6.6133
12	40	12	5	7.0456	7.0767	6.8235	6.7267
13	40	9	3	7.1451	7.4467	7.0946	5.6633
14	40	9	3	7.0814	7.1933	7.035	5.33
15	40	9	3	7.1245	7.3733	7.3476	5.4233

CV (mm/min) = 4.16 + 0.024 T_{on} + 0.323 T_{off} + 0.687 I - 0.00169 T_{on} * T_{on} - 0.0229 T_{off} * T_{off} - 0.2495 I * I + 0.00022 T_{on} * T_{off} + 0.0281 T_{on} * I + 0.0151 T_{off} * I (5)

SR (μm) = 24.34 - 0.6188 T_{on} - 1.457 T_{off} - 0.792 I + 0.00519 T_{on} * T_{on} + 0.0333 T_{off} * T_{off} + 0.0846 I * I + 0.02203 T_{on} * T_{off} + 0.01225 T_{on} * I + 0.0081 T_{off} * I (6)

Table 7 shows the ANOVA analysis for CV and SR of AZ31 HT at 3 hours and 5 hours, and from the analysis, it is found interaction effect of T_{on} * I play a significant role in the CV of both heats treated AZ31 materials. And interaction effect of T_{on} * T_{off} plays a significant role in SR of both heats treated AZ31 materials. The model in table 8 is adequate as evidenced by the lower value of S and higher value of R^2 [14]. Since this model was developed at a 95% confidence level so p-value which is lower than 0.05 shows a significant model.

Table 8: Model summary for CV and SR of AZ31 HT at 3 hours and 5 hours.

	HT at 3 hours		HT at 5 hours	
	CV	SR	CV	SR
S	0.355870	0.277750	0.407769	0.201799
R^2	95.47%	96.48%	93.54%	97.16%
R^2 (Adj)	87.32%	90.14%	81.91%	92.05%

Results and Discussion

Parametric analysis of AZ31 HT at 3 hours

Figure 3 illustrate the combined effect of T_{on} and I on CV by taking T_{off} equal to 9 μs for AZ31 heat treated for 3 hours. From figure 3 it is clear that when T_{on} increases from 30 to 50 μs at 1 amp current then CV decrease by 37.7%, because as shown in ANOVA table 7, current plays significant role in CV. At low pulse current, the discharge energy is small and increase of pulse on time expand the plasma channel which results in decrease of MRR thus reducing the CV. And when T_{on} increases from 30 to 50 μs at 5 amp then CV increases by 7.8%. And when current increases from 1 to 5 amp at T_{on} 30 μs then CV increases by 3.6% and at T_{on} 50μs CV increases by 79.4%. And at T_{on} 50 μs and I 5 amp it shows the maximum CV.

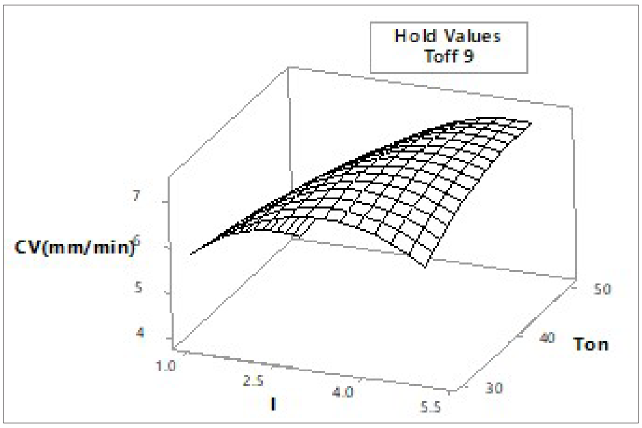

Figure 3: Effect of T_{on} and I on CV.

And figure 4 illustrate the effect of T_{on} and T_{off} on SR for AZ31 heat treated at 3 hours. And it is found that when T_{on} increases from 30 to 50 μs at current maintain at 3 amp and T_{off} at 6 μs then SR increases by 42.39%. And when T_{on} increases from 30 to 50 μ by maintaining I 3 amp and T_{off} 12 μs then SR increases by 1.3%. And when T_{off} increases from 6 to 12 μs by maintaining I 3 amp and T_{on} 30 μs then SR increases by 38.7%. And when T_{off} increases from 6 to 12 μs by maintaining I 3 amp and T_{on} 50 μs then SR decreases by 1.31%. And at lower T_{on} and T_{off}, SR is minimal.

Parametric analysis of AZ31 HT at 5 hours

Figure 5 illustrate the combined effect of T_{on} and I on CV by taking T_{off} equal to 9 μs for AZ31 heat treated for 5 hours.

Table 7: ANOVA for CV and SR of AZ31 HT at 3 hours and 5 hours.

		HT at 3 hours				HT at 5 hours			
		CV		SR		CV		SR	
Source	DF	f-value	p-value	f-value	p-value	f-value	p-value	f-value	p-value
Model	9	11.72	0.007	15.21	0.004	8.04	0.017	19.02	0.002
Linear	3	19.91	0.003	29.12	0.001	13.99	0.007	28.12	0.001
T_{on}	1	2.73	0.159	38.59	0.002	2.84	0.153	19.65	0.007
T_{off}	1	0.00	0.997	7.51	0.041	0.53	0.497	3.83	0.108
I	1	57.00	0.001	41.27	0.001	38.59	0.002	60.87	0.001
Square	3	10.00	0.015	11.54	0.011	7.55	0.026	12.59	0.009
T_{on} * T_{on}	1	3.20	0.133	5.78	0.061	0.63	0.463	24.45	0.004
T_{off} * T_{off}	1	0.57	0.483	3.60	0.116	0.94	0.376	8.12	0.036
I * I	1	28.00	0.003	28.82	0.003	22.12	0.005	10.39	0.023
2-way interaction	3	5.24	0.053	4.98	0.058	2.59	0.165	16.34	0.005
T_{on} * T_{off}	1	0.01	0.940	14.15	**0.013**	0.00	0.976	42.89	**0.001**
T_{on} * I	1	15.63	**0.011**	0.46	0.528	7.58	**0.040**	5.90	0.060
T_{off} * I	1	0.09	0.776	0.31	0.601	0.20	0.676	0.23	0.652

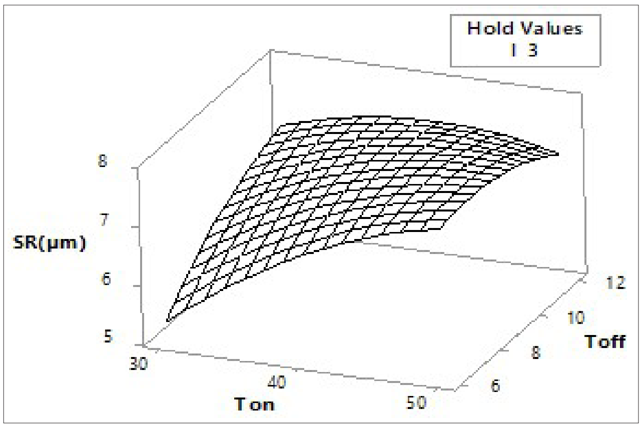

Figure 4: Effect of T_{on} and T_{off} on SR.

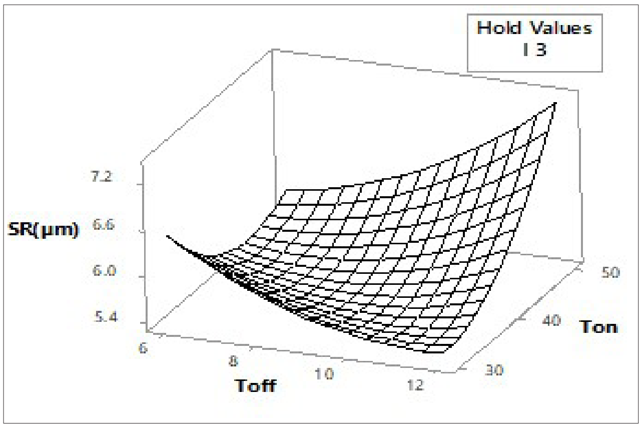

Figure 6: Effect of T_{on} and T_{off} on SR.

From figure 5 it is clear that when T_{on} increases from 30 to 50 µs at 1 amp current and T_{off} 9 µs then CV decrease by 35.3%. And when T_{on} increases from 30 to 50 µs at 5 amp Current and T_{off} 9 µs then CV increases by 0.538%. And when current increases from 1 to 5 amp at T_{on} 30 µs then CV increases by 9% and at T_{on} 50 µs CV increases by 69.4%. And at T_{on} 50 µs and I 5 amp it shows the maximum CV.

And figure 6 illustrate the effect of T_{on} and T_{off} on SR for AZ31 heat treated at 5 hours. And it is found that when T_{on} increases from 30 to 50 µs at current maintain at 3 amp and T_{off} at 6 µs then SR decreases by 11.67%. And when T_{on} increases from 30 to 50 µs by maintaining I 3 amp and T_{off} 12 µs then SR increases by 33.78%. And when T_{off} increases from 6 to 12 µs by maintaining I 3 amp and T_{on} 30 µs then SR decreases by 12.2%. And when T_{off} increases from 6 to 12 µs by maintaining I 3 amp and T_{on} 50 µs then SR increases by 32.82%. And at higher T_{on} and lower T_{off}, SR is minimal.

Conclusions

In this study two AZ31 Mg alloy of 10 mm thickness were heat treated for 3 and 5 hours. Experiments were conducted on WEDM using molybdenum wire electrode on these heat-treated Mg alloys. The effects of T_{on}, T_{off}, and I on output parameters of CV and SR were investigated through the developed RSM model using the BBD approach. After analyzing all the data there are some conclusions which are as follows.

- CV is maximum for both heat-treated AZ31 Mg alloys when the WEDM process is performed at higher T_{on} (50 µs) and current (5 amp).
- When T_{on} increases at 5 amp both CV and SR are showing increasing trend. But when T_{on} increases from 30 to 50 µs at 1 amp, CV shows decreasing trend because as shown in ANOVA table 7, current plays significant role in CV.
- On increasing current, CV also increases.
- In case of AZ31 heat treated for 3 hours, increase of T_{on} increases SR continuously increases but for the sample heat treated for 5 hours SR firstly decreases and after that it further increases.
- SR decreases due to rise in T_{off}.

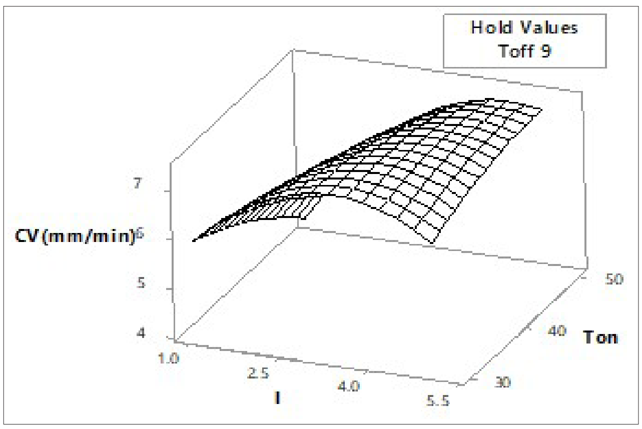

Figure 5: Effect of T_{on} and I on CV.

Acknowledgments

The All India Council for Technical Education's (AICTE) 2019-20 Research Pro-motion Scheme (File No. 8-104/FDC/RPS(POLICY-1)/2019-20) funding help is gratefully acknowledged by the writers.

Conflict of Interest

No potential conflict of interest.

Credit Author Statement

Dhirendra Pratap Singh: Conceptualization, Methodology, Writing - original draft preparation, Writing - review and editing; Chandra Prakash Pandey: Conceptualization, Experimentation, Writing - original draft preparation, Writing - review and editing; Sanjay Mishra: Conceptualization, Data analysis, Validation, Supervision, Writing - original draft preparation, Writing - review and editing. All the authors read and approved the manuscript.

References

1. Liao H, Kim J, Lee T, Song J, Peng J, et al. 2020. Effect of heat treatment on LPSO morphology and mechanical properties of Mg–Zn–Y–Gd alloys. *J Magnes Alloy* 8(4): 1120-1127. https://doi.org/10.1016/j.jma.2020.06.009

2. Chen H, Tang J, Gong W, Gao Y, Tian F, et al. 2021. Effects of annealing treatment on the microstructure and corrosion behavior of hot rolled AZ31 Mg alloy. *J Mater Res Technol* 15: 4800-4812. https://doi.org/10.1016/j.jmrt.2021.10.099

3. Zhang R, Cai S, Xu G, Zhao H, Li Y, et al. 2014. Crack self-healing of phytic acid conversion coating on AZ31 magnesium alloy by heat treatment and the corrosion resistance. *Appl Surf Sci* 313: 896-904. https://doi.org/10.1016/j.apsusc.2014.06.104

4. Das S, Barekar NS, El Fakir O, Wang L, Rao AP, et al. 2015. Effect of melt conditioning on heat treatment and mechanical properties of AZ31 alloy strips produced by twin roll casting. *Mater Sci Eng A* 620: 223-232. https://doi.org/10.1016/j.msea.2014.10.019

5. Köklü U, Koçar O, Morkavuk S, Giasin K, Ayer Ö. 2022. Influence of extrusion parameters on drilling machinability of AZ31 magnesium alloy. *Proc Inst Mech Eng E J Process Mech Eng* 236(5): 2082-2094. https://doi.org/10.1177/09544089221080820

6. Goyal KK, Sharma N, Dev Gupta R, Singh G, Rani D, et al. 2022. A soft computing-based analysis of cutting rate and recast layer thickness for AZ31 alloy on WEDM using RSM-MOPSO. *Materials* 15(2): 635. https://doi.org/10.3390/ma15020635

7. Tapadar J, Thakur R, Chetia P, Tamang SK, Samanta S. 2017. Modeling of WEDM parameters while machining Mg-SiC metal matrix composite. *Mech Eng* 8(5): 878-886. https://doi.org/10.14716/ijtech.v8i5.870

8. Vijayabhaskar S, Rajmohan T. 2019. Experimental investigation and optimization of machining parameters in WEDM of nano-SiC particles reinforced magnesium matrix composites. *Silicon* 11(4): 1701-1716. https://doi.org/10.1007/s12633-017-9676-0

9. Chaudhari R, Vora JJ, Patel V, Lacalle LLD, Parikh DM. 2020. Effect of WEDM process parameters on surface morphology of nitinol shape memory alloy. *Materials* 13(21): 4943. https://doi.org/10.3390/ma13214943

10. Singh DP, Mishra S, Yadav SKS, Porwal RK, Singh V. 2022. Comparative analysis and optimization of thermoelectric machining of alumina and silicon carbide-reinforced aluminum metal matrix composites using different electrodes. *J Adv Manuf Syst* 1-29. https://doi.org/10.1142/S0219686723500191

11. Goyal KK, Sharma N, Gupta RD, Gupta S, Rani D, et al. 2022. Measurement of performance characteristics of WEDM while processing AZ31 Mg-alloy using Levy flight MOGWO for orthopedic application. *Int J Adv Manuf Technol* 119(11-12): 7175-7197. https://doi.org/10.1007/s00170-021-08358-8

12. Gurgenc T, Altay O. 2022. Surface roughness prediction of wire electric discharge machining (WEDM)-machined AZ91D magnesium alloy using multilayer perceptron, ensemble neural network, and evolving product-unit neural network. *Mater Test* 64(3): 350-362. https://doi.org/10.1515/mt-2021-2034

13. Carlini GC, da Silva C, Torres RD, Soares P, Weingaertner WL, et al. 2022. WED-machining performance by reciprocating molybdenum wire on Inconel 718 with water or hydrocarbon dielectrics. *Int J Adv Manuf Technol* 119: 1853-1866. https://doi.org/10.1007/s00170-021-08386-4

14. Mishra YK, Mishra S, Jayswal SC. 2022. Comparative analysis of grey relational analysis integrated with the principal component analysis and analytic hierarchy process for multiobjective optimization of inclined laser percussion drilling in carbon fiber reinforced composites. *J Adv Manuf Syst* 21(01): 1-23. https://doi.org/10.1142/S0219686721500475